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THE GEO-CONTROL SYSTEM FOR STATION KEEPING AND COLOCATION OF GEOSTATIONARY SATELLITES

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ABSTRACT

GeoControl is a compact but powerful and accurate software system for station keeping of single and colocated satellites, which has been developed at the German Space Operations Center. It includes four core modules for orbit determination (including maneuver estimation), maneuver planning, monitoring of proximities between colocated satellites and interference and event prediction. A simple database containing state vector and maneuver information at selected epochs is maintained as a central interface between the modules. A menu driven shell utilizing form screens for data input serves as the central user interface. The software is written in Ada and Fortran and may be used on VAX workstations or mainframes under the VMS operating system.

Key Words: Station keeping, colocation, geostationary satellites, software.

1. INTRODUCTION

Control centers of geostationary satellites are facing a situation today which is considerably different from that experienced one decade ago. Most satellites have to be controlled within narrow boxes of $\pm 0.1^\circ$ width and many owners even intend to reduce the control box to $\pm 0.05^\circ$ to keep a satellite within the field of view of non-steerable Ku-band antennae. At the same time, the continued effort to improve and extend the international satellite telecommunication network has almost led to an overpopulation of certain parts of the geostationary ring. In Europe, for example, the World Administrative Radio Conference (WARC) has assigned common longitude slots for up to eight satellites from different nations. Furthermore, many satellite owners intend to offer extended direct broadcasting capabilities, which can presently only be

met by placing multiple satellites into a common window. Colocation, i.e. station keeping of multiple satellites in common or adjacent control boxes, has therefore become a major requirement for satellite operations near the turn of the century. The need for an increased station keeping performance is further complemented by the requirement to reduce cost driving factors such as operator work load or software maintenance efforts.

Since presently most of these needs are not met by available software packages, the German Space Operations Center (GSOC) has developed a new system to facilitate and improve station keeping and colocation operations of geostationary satellites (Ref. 1). It is based on GSOC's long-term experience in mission control and operations and meets design criteria like

- reduction of operator effort by a high degree of automation,
- easy usage for operators, spacecraft engineers and analysts,
- visualization of results by elaborate graphical output,
- multi-satellite operations concept,
- high-precision modeling,
- simple overall architecture and
- high software quality standards (Ref. 2).

GeoControl consists of the core modules (ORBIT, MAPLA, EVENT and COLO), which are completely satellite and station independent (Fig. 1). The four modules support the basic tasks of

- orbit prediction and determination including maneuvers
- maneuver planning for regular station keeping, station acquisition, shifts in longitude, proximity avoidance or reorbiting
- ephemeris and event prediction including long-term forecasts of shadow transits and interferences

2. FEATURES

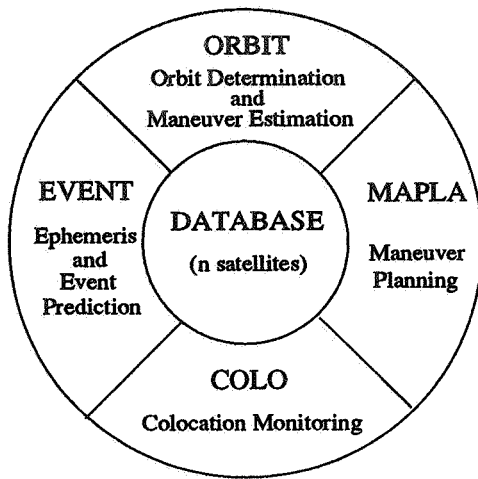


Fig. 1. GeoControl architecture

- relative motion monitoring and proximity analysis

All modules are completely independent of each other and exchange orbit information only via a common state vector and maneuver database. The well-structured architecture of *GeoControl* provides for its easy extension by station and satellite specific software components that may e.g. be required for tracking data preprocessing, antenna steering, maneuver realization or orbit telex generation.

GeoControl is presently employed to control the following satellites:

- TVSat-2 ($-19.2^\circ \pm 0.10^\circ$); loosely collocated with Olympus-1 ($-19.0^\circ \pm 0.10^\circ$) and TDF-1/TDF-2 ($-18.8^\circ \pm 0.10^\circ$);
- Astra-1A and -1B collocated at ($+19.2^\circ \pm 0.10^\circ$); to be collocated with Astra-1C, -1D and -1E in 1993-95;
- DFS-1 ($+23.5^\circ \pm 0.07^\circ$) and DFS-2 ($+28.5^\circ \pm 0.07^\circ$); supplemented by DFS-3 ($+33.5^\circ \pm 0.07^\circ$) in 10/92.

GeoControl has further been used to support the launch and early orbit phase and the station acquisition of Eutelsat II-F1, -F2, -F3 and -F4 (see Ref. 3) and DFS-3.

2.1 Orbit Determination

The ORBIT program provides orbit determination and impulsive Δv estimation capabilities for transfer orbit, drift orbit and on-station operations. Supported tracking data types include Azimuth/Elevation and X/Y-angles in addition to range and two-way Doppler measurements. Precision orbit and measurement modeling ensures an accuracy that is only limited by tracking capabilities and on-board attitude thruster activities (Fig. 2).

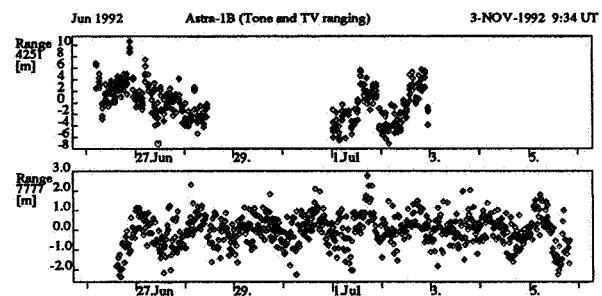


Fig. 2. Sample residuals plot illustrating meter-level orbit determination accuracy obtained over a 9 days tracking arc for Astra-1B. (Top: Tone-ranging system. Bottom: TV-ranging system.)

Individual maneuver components can be estimated during an orbit determination along with orbital elements, radiation pressure coefficients and measurement bias values. This allows for a preliminary maneuver calibration with as little as 3-6 hours of tracking data after a maneuver and enables a fast response in case of maneuver execution errors.

Important results are presented in comprehensive graphs (residuals plots (Fig. 2), station keeping plots (Fig. 3), station acquisition plots) and an orbit determination summary sheet to keep text output to a minimum. These features not only result in an acceleration of operational procedures but also in a considerable reduction of the amount of data that has to be archived for off-line mission analyses.

2.2 Maneuver Planning

The MAPLA program plans the velocity increments and times of impulsive maneuvers for a full station keeping cycle in a single run. Up to three

East/West and two North/South maneuvers per cycle are computed analytically from the difference of predicted orbital elements and target elements at the cycle end. Target elements may either be based on a built-in station keeping strategy or provided manually by the user to support all types of regular and non-regular maneuvers (e.g. shifts in longitude). Maneuver time constraints and deterministic cross-couplings are considered in the maneuver planning process to meet the needs of precision station keeping and colocation with realistic thruster systems (Ref. 4).

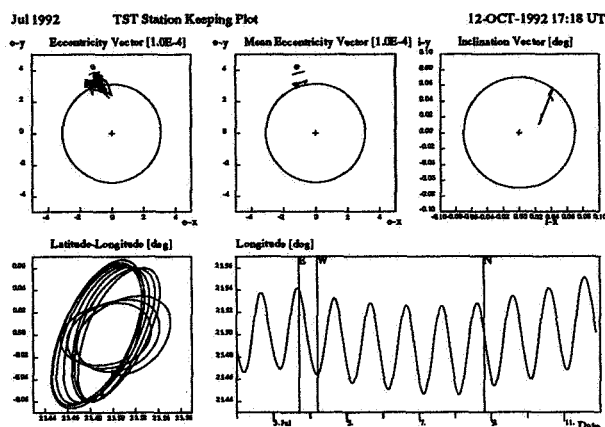


Fig. 3. Sample station keeping plot

Maneuver planning results are summarized in a station keeping plot (Fig. 3) for immediate valuation by the operator. It illustrates the satellite's motion with respect to the longitude and latitude deadband together with the evolution of the eccentricity and inclination vectors. The station keeping plot therefore provides a convenient visualization of all quantities that are required to assess the evolution of the satellite orbit and the impact of planned station keeping maneuvers.

2.3 Ephemeris and Event Prediction

Ephemeris and event predictions required during on-station operations may conveniently be generated by the EVENT program. Supported products include

- Cartesian and Keplerian ephemerides,
- antenna pointing predictions,
- Sun-spacecraft-Earth and Moon-s/c-Earth angle predictions,
- true spacecraft local time computation,

- window violation warnings,
- predictions of Earth or Moon shadow transits,
- predictions of Sun or Moon interferences with infrared Earth sensors (Fig. 4),
- predictions of Sun interferences with the ground station antenna beam.

The generation of station keeping plots (Fig. 3) over a sequence of cycles is, furthermore, supported for long-term maneuver planning and easy report generation.

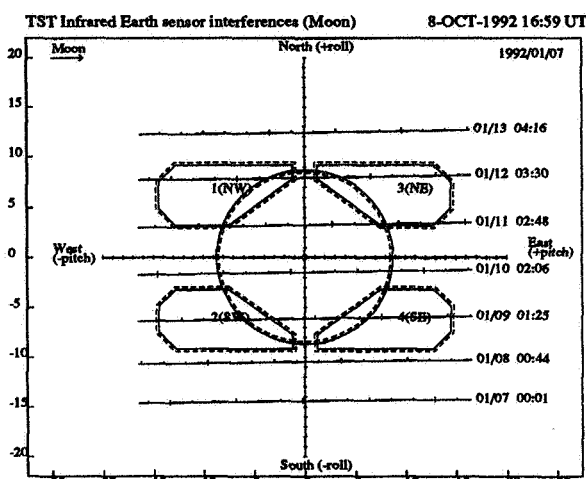


Fig. 4. Sample sensor interference plot

Aside from basing a prediction on the best-known orbit and maneuver database the user may choose a center-of-box ephemeris for long-term forecasts. Approximate shadow transits or Sun/Moon interferences can thus be predicted long in advance before the actual or planned satellite orbit is known.

2.4 Colocation

As mentioned in the introduction, colocation operations are supported as an integrated feature of the *GeoControl* system. This is achieved by the design of the MAPLA maneuver program and by the dedicated COLO program.

By means of appropriate target element biases, MAPLA may be used to implement different types of separation strategies (e.g. longitude or eccentricity/inclination separation) without loosing the freedom to plan each satellite's maneuvers independently. Similarly MAPLA may be used to compute evasive maneuvers that may e.g. be required after maneuver failures or during close approaches

with uncontrolled satellites in the event of a longitude shift. Colocation operations can thus be performed at a modest increase of operator workload compared to station keeping of individual satellites.

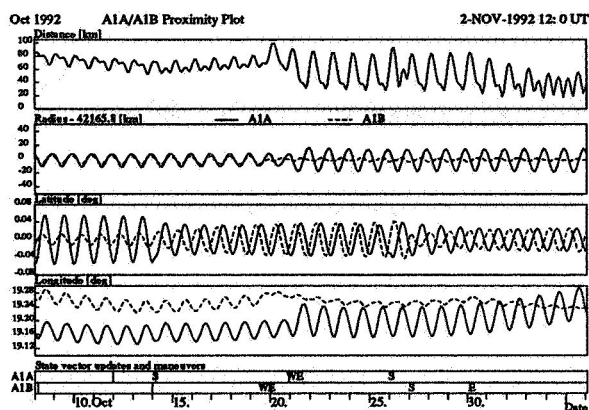


Fig. 5. Sample relative motion plot for colocated satellites

The MAPLA maneuver planning program is supplemented by the COLO relative motion monitoring program. It supports the detection and valuation of proximities in case of longitude swap or colocated satellites. Both text and graphics information is provided for detailed analyses and avoidance maneuver planning. A sample relative motion plot representing the switch of ASTRA-1A and 1B from the longitude to the eccentricity and inclination separation colocation strategy is shown in Fig. 5.

3. THE GEO-CONTROL DATABASE

The open architecture of the *GeoControl* system is based on the concept of an orbit and maneuver database, which serves as the only interface between different programs. All core modules have internal capabilities for generating a satellite's trajectory from state vector and maneuver information. Thus *GeoControl* does not require any interface ephemeris files. The database itself is a fixed format ASCII text file that can easily be read and modified by a standard text editor and no commercial database software (dBase, Oracle) is therefore required to maintain the database.

Two different functional types of database files are maintained within *GeoControl* to meet the needs of practical station keeping operations. A *scratch* database is allocated for each satellite, which collects database records generated by the ORBIT

and MAPLA programs in the course of an orbit determination or maneuver planning. The records created by these programs are appended to the scratch database, which thus contains an incremental log of all results obtained by the operator during a station keeping cycle. In addition to the scratch database, the *GeoControl* system supports a *best-knowledge* database, which provides a time ordered sequence of database records that represent the best orbit information available for contiguous time intervals. The maintenance of the best-knowledge database is supported by an interactive program that allows the user to select a database record from the scratch database and insert it into the best-knowledge database. The program automatically inserts the record at the appropriate position and replaces existing records covering the same time slot. Thus, the best-knowledge database contains the full history of the satellite orbit in a compact format and allows for a simple generation of ephemerides, event lists, station keeping plots and relative motion plots over arbitrary periods of time when using the EVENT and COLO programs.

4. USER INTERFACE

The core programs of the *GeoControl* system are operated via command files and can be executed as batch or foreground jobs. The operator's interaction with *GeoControl* is essentially limited to the menu driven configuration of the job command files using a fully interactive, forms-oriented setup creation software.

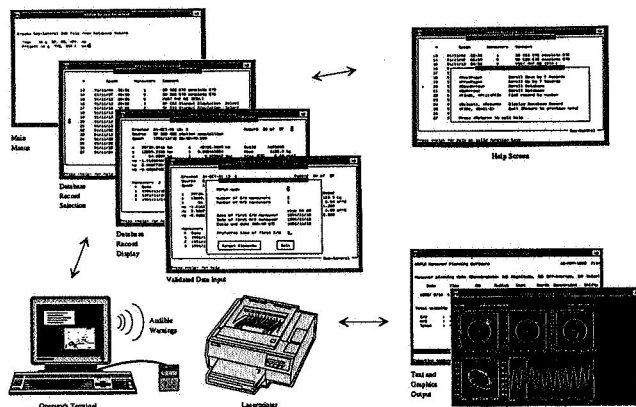


Fig. 6. Interactive *GeoControl* user interface

This software allows the user to select an epoch state vector from the orbit database and enter

those parameters that have to be changed from one run of the software to the next (e.g. the tracking interval for an orbit determination). Input parameters that have to be modified at rare instances only are stored in template setup files. All menus and input forms are implemented using DECforms, which provides for easy usage and elaborate input validation.

5. SYSTEM REQUIREMENTS

GeoControl may be installed on arbitrary VAX workstations or multi-user systems running the VMS operating system with a minimum of 4 MB core memory and 20 000 blocks of free disk space. The system may be operated from workstation consoles and alpha terminals. DEC Ada, DEC Fortran and DECforms are required to rebuild the software from the source code, which is delivered with the software. A run-time license for DECforms is required on each machine running *GeoControl*. All graphics output is generated in PostScript language by a built-in graphics package and can be printed on standard laser printers or displayed on workstation terminals. Other graphics packages like the GKS Graphical Kernel System can be supported as an option.

6. OPERATIONAL EXPERIENCE AT SES

The present section summarizes the experience of the Société Européenne des Satellites (SES) in using *GeoControl* for the station-keeping of the ASTRA satellites. The ASTRA spacecraft are three-axis stabilized direct broadcasting TV satellites colocated at the orbital position of $+19.2^\circ \pm 0.10^\circ$ East longitude. ASTRA-1A (a GE Series 4000) was launched in December 1988 and ASTRA-1B (a GE Series 5000) was launched in March 1991. The future plans of SES are to extend the present configuration to four colocated satellites. The next two satellites, ASTRA-1C, 1D and 1E, will be Hughes HS-601 spacecraft to be launched in 1993, 1994 and 1995, respectively.

After a trial phase of three months that started in January 1992 and during which efficient training and support have been provided by GSOC, *GeoControl* has become the primary station-keeping software used by SES. During this trial phase, *GeoControl* has been run in parallel with other station-keeping softwares and has proved superior

to those in terms of the various design criteria listed in the introduction.

In particular the open architecture of the software and database concept described in section 3 have been greatly appreciated. The user interface has proved effective and the extremely reduced number of steps required to generate any kind of output results (plots, summary sheets, detailed outputs) confirmed superiority of *GeoControl* in terms of operations workload.

As already mentioned in section 2.1, orbit determinations performed based on tracking data from a high precision TV-ranging device demonstrated the accuracy of the propagator used by the ORBIT program. In the context of colocation another key advantage of ORBIT is the ability to evaluate the performance of maneuvers shortly after their execution, which increases operations safety. Finally, a remarkable feature of the orbit determination module is that it allows to solve for *two* components of the solar radiation force (along and normal to the Sun-spacecraft line). This greatly improves orbit determination accuracies in the case of ASTRA-1A, whose solar panels are not directly facing the Sun.

The capability of MAPLA to take deterministic cross-coupling into account in maneuver computations also proved to be an important advantage for the colocation of three-axis stabilized spacecraft. In the particular case of the ASTRA satellites, which are of different designs, the independence of the MAPLA module from the peculiarities of thruster systems is essential. By contrast to most orbital softwares *GeoControl* also offers a sufficiently general maneuver planning concept to support different station keeping strategies. As an illustration, MAPLA allows eccentricity and longitude control of the ASTRA satellites by alternating station-keeping cycles using single and double East/West corrections. The flexibility of MAPLA also clearly appeared when the colocation strategy used to colocate ASTRA-1A and 1B was changed from longitude separation to eccentricity and inclination separation in October 1992. Proper setting of parameters permitted MAPLA to compute the maneuvers required to proceed with the configuration switch as well as regular station-keeping maneuvers in the case of both strategies.

The transition from one strategy to another is illustrated by the relative motion plot of Fig. 5. In addition to such plots the relative motion monitoring program COLO produces text output con-

taining an analysis of the intersatellite separation in terms of the error ellipsoid concept. This allows actual tracking, orbit determination and expected maneuver errors to be taken into account in the evaluation of the separation safety.

To summarize, usage of *GeoControl* at SES confirmed that the software has been designed on the basis of a long-term experience in station-keeping of geostationary satellites and includes state-of-the-art station-keeping and colocation techniques. Finally, the application of high software quality standards, resulting in simple maintainability and installation of *GeoControl* and highly understandable code, has been greatly appreciated by SES.

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